Environmental Technology Verification

Test Report of Mobile Source Emissions Control Devices

Donaldson Company, Inc.
Series 6000 Diesel Oxidation Catalyst Muffler and
Spiracle™ Closed Crankcase Filtration System

Prepared by

Southwest Research Institute

Research Triangle Institute

Under a Cooperative Agreement with
U.S. Environmental Protection Agency

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MOBILE DIESEL ENGINE AIR POLLUTION CONTROL**
APPLICATION:	**CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN HIGHWAY USE BY DIESEL OXIDATION CATALYSTS AND CRANKCASE EMISSIONS CONTROL**
TECHNOLOGY NAME:	**DONALDSON COMPANY, INC. SERIES 6000 DIESEL OXIDATION CATALYST MUFFLER AND SPIRACLE CLOSED CRANKCASE FILTRATION SYSTEM**
COMPANY:	**DONALDSON CO., INC.**
ADDRESS:	**1400 WEST 94TH STREET MINNEAPOLIS, MN 55431-2370 PHONE: (952) 887-3730 FAX: (952) 887-3937**
WEB SITE:	**http://www.donaldson.com**
E-MAIL:	**imes@mail.donaldson.com**

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups, which consist of buyers, vendor organizations, permitters, and other interested parties; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Air Pollution Control Technology Verification Center (APCTVC), one of six centers under the ETV Program, is operated by Research Triangle Institute (RTI), in cooperation with EPA's National Risk Management Research Laboratory. The APCTVC has evaluated the performance of an emissions control system consisting of an exhaust oxidation catalyst and crankcase emission control device for mobile diesel engines, the Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler, Series 6000 Catalyst Formulation, and the Spiracle™ Closed Crankcase Filtration System.

ETV TEST DESCRIPTION

All tests were performed in accordance with the general test plan *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, PM Filters, and Engine Modification Technologies for Highway and Nonroad Use Diesel Engines* and the Test-Specific Addendum to ETV Mobile Source Test/QA Plan for the Donaldson Company, Inc. diesel oxidation catalyst muffler and Spiracle™. These documents are written in accordance with the applicable generic verification protocol and include requirements for quality management, quality assurance, procedures for product selection, auditing of the test laboratories, and test reporting format.

The mobile diesel engine air pollution control technology was tested at Southwest Research Institute. The performance verified was the percentage emission reduction achieved by the technology for particulate matter (PM), nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) relative to the performance of the same baseline engine without the technology in place. The percentage emission reduction is relative to the total emissions from the tailpipe and crankcase vent. Operating conditions were documented and ancillary performance measurements were also made. A summary description of the ETV test is provided in Table 1.

Table 1. Summary Description of the ETV Test

Test Type	Highway Transient Federal Test Procedure (FTP), heavy-duty cycle
Engine Family	WDDXH12.7EGD
Engine Make–model year	Detroit Diesel Corporation Series 60–1998
Service Class	Heavy Duty Diesel
Engine Rated Power	299 kW (400 bhp) @ 1,800 rpm
Engine Displacement	12.7 L
Technology	Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler, Series 6000 Catalyst and Spiracle™ Closed Crankcase Filtration System
Technology description	A ceramic oxidation catalyst matrix wash-coated with catalyst, packaged in a muffler-sized can for retrofit installation by a moderately skilled mechanic. Blow-by filter in a closed-loop configuration. No engine modifications required.
Test cycle or mode description	One cold-start and three hot-start tests according to FTP test plus measurement of baseline crankcase particulate emissions
Test fuel description	EPA standard low-sulfur and ultralow-sulfur No. 2 diesel fuels per 40 CFR Part 86.1313
Critical measurements	PM, NOx, HC, and CO
Ancillary measurements	NO, CO_2, engine blow-by pressure and exhaust back-pressure, exhaust temperature, fuel consumption, exhaust PM soluble organic fraction (SOF), and crankcase particulate emissions

VERIFIED TECHNOLOGY DESCRIPTION

This verification statement is applicable to the *Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler (Series 6000 Catalyst Formulation) plus Spiracle™ Closed Crankcase Filtration System*. According to the vendor, the Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler with Series 6000 Catalyst Formulation is packaged and marketed for use on diesel engines from 150 to 600 bhp. The unit whose performance was verified had part numbers 5190B2246 and M110940. It is applicable to engines fueled by standard low-sulfur (500 ppm or less) number 2 diesel fuel or ultralow-sulfur (15 ppm or less) diesel fuel. The Donaldson Spiracle™ Closed Crankcase Filtration System uses two filtration stages integrated into a single, replaceable filter cartridge. The system whose performance was verified has part number S040004.

This verification statement describes the performance of the tested technology on the diesel engine and fuels identified in Table 1. The performance was measured for both degreened and aged devices. A degreened device has been operated for a brief period before testing (25 to 125 hours) to achieve a stable emissions reduction. An aged device has been operated for at least 33 percent of its expected full-life.

VERIFICATION OF PERFORMANCE

The Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler (Series 6000) and the Spiracle™ Closed Crankcase Filtration Systems achieved the emissions reduction shown in Table 2 at the stated conditions. The emissions reduction is relative to the total emissions from the tailpipe and crankcase vent.

Table 2. Verified Emissions Reductions for System Consisting of a Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler with Series 6000 Catalyst Formulation and the Spiracle™ Closed Crankcase Filtration System

	Fuel		Mean Emissions Reduction [a] (%)				95% Confidence Limits on the Emissions Reduction (%)			
Device type	Baseline	Controlled	PM	NO_x	HC	CO	PM	NO_x	HC	CO
Degreened	LSD	LSD	26	[b]	52	14	23–30	[b]	23-81	5.1-22
Aged	LSD	LSD	21	[b]	62	12	19-23	[b]	33-90	7.1-18
Degreened	LSD	ULSD	34	[b]	[b]	19	30-38	[b]	[b]	15-24
Degreened	ULSD	ULSD	30	[b]	50	24	24-36	[b]	41-60	20-27

[a] Emissions reduction from baseline of tailpipe plus crankcase emissions.
[b] The emissions reduction could not be distinguished from zero with 95% confidence.

For the purposes of determining the status of the technology in regard to EPA's voluntary diesel retrofit program, the prospective user is encouraged to contact EPA's Office of Transportation and Air Quality (OTAQ) or visit the retrofit program web site at http://www.epa.gov/otaq/retrofit/.

The APCTVC QA Officer has reviewed the test results and quality control data and has concluded that the data quality objectives given in the generic verification protocol and test/QA plan have been attained. EPA and APCTVC quality assurance staff have conducted technical assessments at the test laboratory and of the data handling. These confirm that the ETV tests were conducted in accordance with the EPA-approved test/QA plan.

This verification statement verifies the emissions characteristics of the *Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler (Series 6000) and the Spiracle™ Closed Crankcase Filtration System with diesel fuels* for the stated application. Extrapolation outside that range should be done with caution and an understanding of the scientific principles that control the performance of the technologies. This verification focused on emissions. Potential technology users may obtain other types of performance information from the manufacturer.

In accordance with the generic verification protocol, this verification statement is valid, commencing on the date below, indefinitely for application of *Donaldson Company, Inc. DCM Oxidation Catalyst Muffler (Series 6000) and the Spiracle™ Closed Crankcase Filtration System with diesel fuels* within the range of applicability of the statement.

Original signed by H.W. McKinnon 9/15/03
Hugh W. McKinnon, MD — Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original signed by J.R. Farmer 9/30/03
Jack R. Farmer — Date
Program Director
Air Pollution Control Technology Verification Center

NOTICE: ETV verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and RTI make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of commercial product names does not imply endorsement.

Environmental Technology Verification Report

Mobile Source Retrofit Air Pollution Control Devices

Donaldson Company, Inc.
Series 6000 Diesel Oxidation Catalyst Muffler and
Spiracle™ Closed Crankcase Filtration System

Prepared by

Research Triangle Institute
Southwest Research Institute

EPA Cooperative Agreement No. CR829434-01-1

EPA Project Manager:
Theodore G. Brna
Air Pollution and Control Division
National Risk Management Research Laboratory
Office of Research and Development
Research Triangle Park, NC 27711

September 2003

Notice

This document was prepared by Research Triangle Institute (RTI) and its subcontractor Southwest Research Institute, with partial funding from Cooperative Agreement No. CR829434-01-1 with the U.S. Environmental Protection Agency (EPA). The document has been submitted to RTI/EPA's peer and administrative reviews and has been approved for publication. Mention of corporation names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products.

Foreword

The Environmental Technology Verification (ETV) Program, established by the U.S. Environmental Protection Agency (EPA), is designed to accelerate the development and commercialization of new or improved technologies through third-party verification and reporting of performance. The goal of the ETV Program is to verify the performance of commercially ready environmental technologies through the evaluation of objective and quality-assured data so that potential purchasers and permitters are provided with an independent and credible assessment of the technology that they are buying or permitting.

The Air Pollution Control Technology Verification Center is part of the EPA's ETV program and is operated as a partnership between Research Triangle Institute (RTI) and EPA. The Center verifies the performance of commercially ready air pollution control technologies. Verification tests use approved protocols and verified performance is reported in verification statements signed by EPA. RTI contracts with Southwest Research Institute to perform verification tests on engine emission control technologies.

Retrofit air pollution control devices used to control emissions from mobile diesel engines are among the technologies evaluated by the APCTVC. The APCTVC developed (and EPA approved) the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* to provide guidance on the verification testing of specific products that are designed to control emissions from diesel engines.

The following report reviews the performance of the Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler (Series 6000 catalyst formulation) and Spiracle™ Closed Crankcase Filtration System. ETV testing of this technology was conducted during November 2002 at Southwest Research Institute. All testing was performed in accordance with an approved test/QA plan that implements the requirements of the generic verification protocol at the test laboratory. This report is one of a set of three reports that separately report the performance data from three control device configurations included in the test series.

Availability of Report

Copies of this verification report are available from

- Research Triangle Institute
  Engineering and Technology Division
  P.O. Box 12194
  Research Triangle Park, NC 27709-2194

- U.S. Environmental Protection Agency
  Air Pollution Prevention and Control Division (E305-01)
  109 T. W. Alexander Drive
  Research Triangle Park, NC 27711

Web sites: http://www.epa.gov/etv/verifications/verification-index.html *(electronic copy)*
http://www.epa.gov/ncepihom/

Contents

Figures

Tables

Acronyms/Abbreviations

°F	degrees Fahrenheit
°C	degrees Celsius
APCTVC	Air Pollution Control Technology Verification Center
BFU	blow-by filter unit
BPM	blow-by particulate matter
bhp	brake horsepower
bhp-hr	brake horsepower - hour
BSFC	brake specific fuel consumption
CCC	closed-crankcase configuration
CFR	Code of Federal Regulations
cm	centimeter(s)
CO	carbon monoxide
CO_2	carbon dioxide
DDC	Detroit Diesel Corporation
DOC	diesel oxidation catalyst
EPA	Environmental Protection Agency
ETV	environmental technology verification
FTP	Federal Test Procedure
ft	foot (feet)
g	gram(s)
HC	hydrocarbon(s)
HD	heavy duty
HFID	heated flame ionization detector
bhp	brake horsepower
in.	inch(es)
in. H_2O	inches of water
in. Hg	inches of mercury
kW	kilowatt(s)
kPa	kilopascal(s)
L	liter(s)
Lpm	liters per minute
lb	pound(s)
lb-ft	pound-foot (feet)
LSD	low-sulfur diesel
m	meter(s)
min.	minute(s)
mm	millimeter(s)
N	newton(s)
N-m	newton-meter
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxide
NDIR	nondispersive infrared
OCC	open-crankcase configuration
OTAQ	Office of Transportation and Air Quality
Pa	pascal(s)
PM	particulate matter
ppm	parts per million by volume
QA	quality assurance
QC	quality control
rpm	revolutions per minute
RTI	Research Triangle Institute
SOF	soluble organic fraction
SOP	standard operating procedure
SwRI	Southwest Research Institute
TPM	total particulate matter
ULSD	ultralow-sulfur diesel

Acknowledgments

The authors acknowledge the support of all of those who helped plan and conduct the verification activities. In particular, we would like to thank Theodore Brna, EPA's Project Manager, and Paul Groff, EPA's Quality Assurance Manager, both of EPA's National Risk Management Research Laboratory in Research Triangle Park, NC. We would also like to acknowledge the assistance and participation of all the Donaldson Company, Inc. personnel who supported the test effort.

For more information on the Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler with Series 6000 Catalyst Formulations or the Spiracle™ Closed Crankcase Filtration System, contact:

Julian Imes
Donaldson Company, Inc.
1400 West 94th Street
Minneapolis, MN 55431-2370
Telephone: (952) 887-3730
Fax: (952) 887-3937
Email: imes@mail.donaldson.com
Web site: http://www.donaldson.com

OR

Fred Schmidt
Donaldson Company, Inc.
1400 West 94th Street
Minneapolis, MN 55431-2370
Telephone: (952) 887-3835
Fax: (952) 887-3008
Email: fschmidt@mail.donaldson.com
Web site: http://www.donaldson.com

For more information on verification testing of mobile sources air pollution control devices, contact:

Jenni Elion
Research Triangle Institute
P.O. Box 12194
Research Triangle Park, NC 27709-2194
Telephone: (919) 541-6826
Email: jme@rti.org
Web site: http://etv.rti.org/apct/index.html

Section 1.0
Introduction

This report reviews the performance of the Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler (Series 6000 Catalyst Formulation) and Spiracle™ Closed Crankcase Filtration System. Environmental Technology Verification (ETV) testing of this technology was conducted during a series of tests in November 2002 by Southwest Research Institute (SwRI) under contract with the Air Pollution Control Technology Verification Center (APCTVC). This report addresses one of the three baseline-control device configurations covered by this test series. The objective of the APCTVC and the ETV Program is to verify, with high data quality, the performance of air pollution control technologies. Control of air emissions from diesel engines is within the scope of the APCTVC. An APCTVC program area was designed by Research Triangle Institute (RTI) and a technical panel of experts to evaluate the performance of diesel exhaust catalysts, particulate filters, and engine modification control technologies for mobile diesel engines. Based on the activities of this technical panel, the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* (RTI, 2002)[1] was developed. The specific test/quality assurance plan addendum for the ETV test of the technology submitted by Donaldson Company, Inc. was developed and approved on October 3, 2002.[2] The goal of the test was to measure the emissions control performance of the technology systems and their emissions reductions relative to an uncontrolled engine.

A description of the Donaldson Company, Inc. Diesel Oxidation Catalyst Muffler (Series 6000 Catalyst Formulation) and the Spiracle™ Closed Crankcase Filtration System is presented in Section 2. Section 3 documents the procedures and methods used for the test and the conditions over which the test was conducted. The results of the test are summarized and discussed in Section 4, and references are presented in Section 5.

This report contains only summary information and data as well as the verification statement. Complete documentation of the test results is provided in a separate test report[3] and audit of data quality report.[4] These reports include the raw test data from product testing and supplemental testing, equipment calibration results, and quality assurance (QA) and quality control (QC) activities and results. Complete documentation of QA/QC activities and results, raw test data, and equipment calibration results are retained in Southwest Research Institute's files for seven years.

Section 2.0
Description of Products

The APCTVC conducted verification testing for the Donaldson technology system described below (descriptions were provided by Donaldson Company). The system was assembled from the following products:

- Donaldson Company, Inc. Diesel Oxidation Catalyst (DOC) Muffler with Series 6000 catalyst formulation for use with standard on-road low-sulfur diesel (LSD) fuel (500 ppm maximum sulfur content) and ultralow-sulfur diesel (ULSD) fuel (15 ppm maximum sulfur content), and
- Donaldson Spiracle™ Closed Crankcase Filtration System with two filtration stages integrated into a single, replaceable filter cartridge.

The technology was provided directly to the APCTVC's test organization, Southwest Research Institute, as the following items:

- degreened Donaldson Company, Inc. DOC Series 6000 catalyst formulation (part number 5190B2246),
- aged Donaldson Company, Inc. DOC Series 6000 catalyst formulation (part number M110940), and
- Spiracle™ closed crankcase ventilation system unit and filter (part number S040004).

The catalyst and Spiracle™ filter were degreened on an engine operated for 25 hours. For the first eight hours, the engine was operated in a repeated cycle with 15 minutes at idle followed by 15 minutes at peak torque speed and loaded to produce 400 °C exhaust gas temperature at the DOC inlet. For the remaining time, the engine was run at the steady state condition of peak torque speed and loaded to produce 400 °C exhaust gas temperature at the DOC inlet. The aged Series 6000 catalyst is from 86,015 miles in production use on a CAT 3126 engine in a Freightliner FL-70 truck.

All testing was conducted on a Detroit Diesel Series 60 engine fueled by conventional No. 2 diesel fuel. Crankcase emissions were separately measured for the baseline tests without the Spiracle™ system installed and were added to the exhaust or tailpipe emissions from those baseline tests to determine the total baseline particulate matter (PM) emissions. With the Spiracle™ system installed, crankcase emissions were filtered and recycled back into the air intake to create a closed crankcase configuration (CCC).

Figure 1. Spiracle™ blow-by filter unit.

The Spiracle™ blow-by filter unit (BFU) consists of a filter housing that includes a blow-by inlet port with a pressure tap, an outlet port with a pressure tap, and an oil drain to the engine oil pan, as shown in Figure 1. A flow regulator is also contained inside the housing at the outlet to control crankcase gas flow pulled into the engine intake system. A one-way flow control valve is mounted in the oil drain line to prevent back-flow of blow-by from the top of the oil pan back to the Spiracle™ BFU. The BFU was used in a CCC to control the blow-by particulate matter (BPM).

Section 3.0
Test Documentation

The ETV testing took place at Southwest Research Institute under contract to the APCTVC. Testing was performed in accordance with:

- *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines,*[1]
- *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines,*[5] and
- *Test-Specific Addendum to ETV Mobile-Source Test/QA Plan for Donaldson Company, Inc. DOC Converter Muffler*.[2]

The applicant had reviewed the generic verification protocol and had an opportunity to review the test/QA plan prior to testing.

3.1 Engine Description

The ETV testing was performed on a 1998 Detroit Diesel Corporation Series 60 heavy-duty diesel engine. The engine was an in-line six-cylinder with a 12.7 liter (L) displacement and rated for 400 bhp at 1,800 rpm. It was turbocharged and used a laboratory water-to-air heat exchanger for a charge air aftercooler. The engine was originally manufactured with a crankcase breather tube (open crankcase) which normally vents blow-by gases (including PM) to the atmosphere. The engine was owned by SwRI and has been used on various research programs.

Table 1 provides the engine identification details. The baseline engine is shown in Figure 2.

Table 1. Engine Identification Information

Engine serial number	06R0422316
Date of manufacture	April 1998
Make	Detroit Diesel Corporation (DDC)
Model year	1998
Model	Series 60, 6067TK60
Engine displacement and configuration	12.7 L, Inline 6
Service class	On-highway, heavy-duty (HD) diesel engine
EPA engine family identification	WDDXH12.7EGD
Rated power	400 bhp at 1,800 rpm
Rated torque	1,550 lb-ft at 1,200 rpm
Certified emission control system	Electronic control
Aspiration	Turbocharged, air-to-air intercooled
Fuel system	Direct injection, electronically controlled unit injectors
Electronic control module	DDEC-III

Figure 2. Baseline engine: a 1998 Detroit Diesel Corporation heavy-duty diesel engine, mounted in Southwest Research Institute's engine test cell #4.

3.2 Engine Fuel Description

Two different diesel fuels were used during this verification test; a conventional, on-road No. 2 LSD fuel and a No. 2 ULSD fuel. The sulfur levels for these fuel batches were 346 ppm and 8 ppm, respectively. The fuels meet current EPA diesel fuel specifications given in 40 CFR §86.1313-98, Table N98-2[6] for LSD fuel and 40 CFR § 86.1313-2007, Table N07-2[7] for ULSD fuel. Table 2 summarizes selected fuel properties from the suppliers' analyses.

3.3 Summary of Emissions Measurement Procedures

The ETV tests consisted of baseline uncontrolled tests and tests with the control system installed. The baseline engine was tested on conventional LSD and ULSD fuels. The standard heavy duty (HD) Transient Federal Test Procedure[8] (FTP) for exhaust emissions testing was performed, and crankcase emissions were measured with the engine in the open-crankcase (OCC) and crankcase emission measurement system installed. The Donaldson DOC Series 6000 catalyst formulation was then installed, along with the Spiracle™ system. The installed parts were conditioned using three FTP cycles before they were set up for the cold-start test.

The engine test cycle for the DOC muffler verification testing was the heavy-duty FTP cycle. These tests were official tests with one cold- and three hot-start transient cycles conducted in accordance with the test/QA plan.[5] Individual exhaust gas and PM samples were taken for each cycle, and a soluble organic fraction (SOF) analysis was performed on the baseline engine exhaust PM samples.

Table 2. Selected Fuel Properties and Specifications

Item	Code of Federal Regulations Specification[a]		Test Fuel	
	ASTM	Type-2D	"LSD" EM-4712-F	"ULSD" EM-4579-F
Cetane number	D613	40–50	46.0	47.4
Cetane index	D976	40–50	47.3	47.5
Distillation range:				
Initial boiling point, °F (°C)	D86	340–400 (101–204)	365 (185)	364 (184)
10% Point, °F (°C)	D86	400–460 (204–238)	427 (219)	401 (205)
50% Point, °F (°C)	D86	470–540 (243–282)	510 (266)	488 (253)
90% Point, °F (°C)	D86	560–630 (293–332)	587 (308)	588 (309)
End point, °F (°C)	D86	610–690 (321–366)	633 (334)	665 (352)
Gravity (American Petroleum Institute)	D287	32–37	35.17	36.95
Specific gravity		–	0.8490	0.840
Total sulfur, ppm	D2622	(300–500)[b] (7-15)[c]	346	8.47
Hydrocarbon composition:				
Aromatics (min.), %	D1319	27	29.2	27.5
Paraffins, naphthenes, and Olefins, %	D1319	[d]	70.8	72.5
Flash point (min.), °F (°C)	D93	130 (54)	164 (73)	155 (68)
Viscosity, centistokes @ 40 °C	D445	2.0–3.2	2.6	2.2
Fuel supplier	–	–	Chevron Phillips Chemical Co.	

[a] Diesel fuel specification as in CFR 40 86.1313-98(b)(2) for the year 1998 and beyond and CFR 40 86.1313-2007(b)(2) for the year 2007 and beyond, for heavy-duty diesel engines.
[b] 1998 sulfur range specification.
[c] 2007 sulfur range specification.
[d] Remainder of the hydrocarbons.

The testing included tailpipe and crankcase emissions testing using both the OCC and CCC. Spiracle™, Donaldson's product for filtering engine crankcase emissions, was used during the CCC. The OCC baseline testing was a separate measurement and did not affect the engine exhaust. When the engine was configured in an OCC, the crankcase effluent was routed through a sample filter to allow the collection of the total crankcase particulate. When the engine was configured in a CCC, the crankcase effluent was routed through the Spiracle™ filter before being directed into the intake of the engine.

Blow-By PM Measurement System

Since no EPA standard method was available to measure blow-by PM emissions, SwRI developed a standard operating procedure (SOP) based on a modification of the standard method used for exhaust PM measurements.[9] It consists of a vacuum breaker, a filter holder, and a pump, as shown in Figure 3. The vacuum breaker kept the engine blow-by exit pressure close to ambient pressure at different engine speeds and loads while blow-by sampling was performed. This pressure control was done by allowing excess ambient air to be entrained with the blow-by flow during sampling. The pump drew the blow-by flow and ambient excess air through a filter holder for BPM collection. Based on prior experience of SwRI, a filter efficiency of better than 99 percent was achieved by using a stack of three filters 7 in (18 cm) in diameter with a total thickness of 1.5 in (3.8 cm).

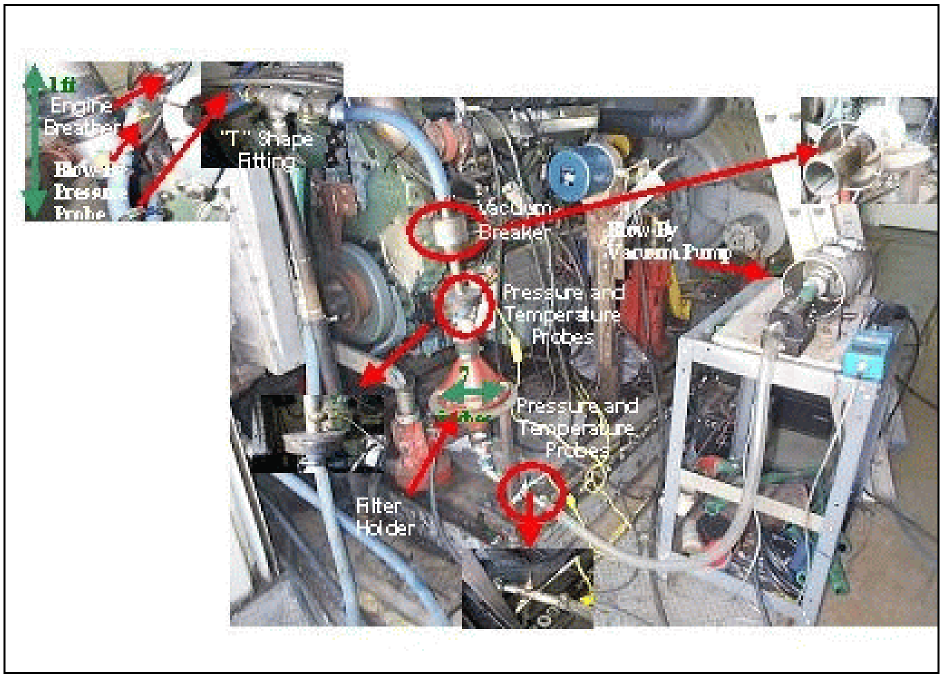

Figure 3. ETV-approved blow-by measurement system for a heavy-duty diesel engine.

Emissions Test Procedures

Exhaust emissions were measured using HD Transient FTP[8] and the experimental setup shown in Figure 4. Dilute exhaust emissions measured during tests over the transient FTP operating conditions included total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_X), nitric oxide (NO), and exhaust PM. BPM was measured using a SwRI SOP[9] for only the OCC. The CO and CO_2 levels were determined using nondispersive infrared (NDIR) instruments. Total HC were measured using continuous sampling techniques that employed a heated flame ionization detector (HFID). The NO_X and NO were measured continuously using two separate chemiluminescent analyzers fed simultaneously from a common path. The nitrogen dioxide (NO_2) was reported as the difference between NO_X and NO.

The exhaust PM level for each test was determined using dilute sampling techniques that collected PM on a pair of 90-mm diameter Pallflex T60A20 filter medium, which were used in series. The particulate filter pair was weighed together both before and after each test to establish exhaust PM emissions for the test. The SOF was determined for engine baseline tests using the same pair of 90-mm filters that were used to determine exhaust PM mass emissions. The extraction process for the SOF used a micro-Soxhlet apparatus with toluene-ethanol solvent, as specified by the California Air Resources Board test method.[10]

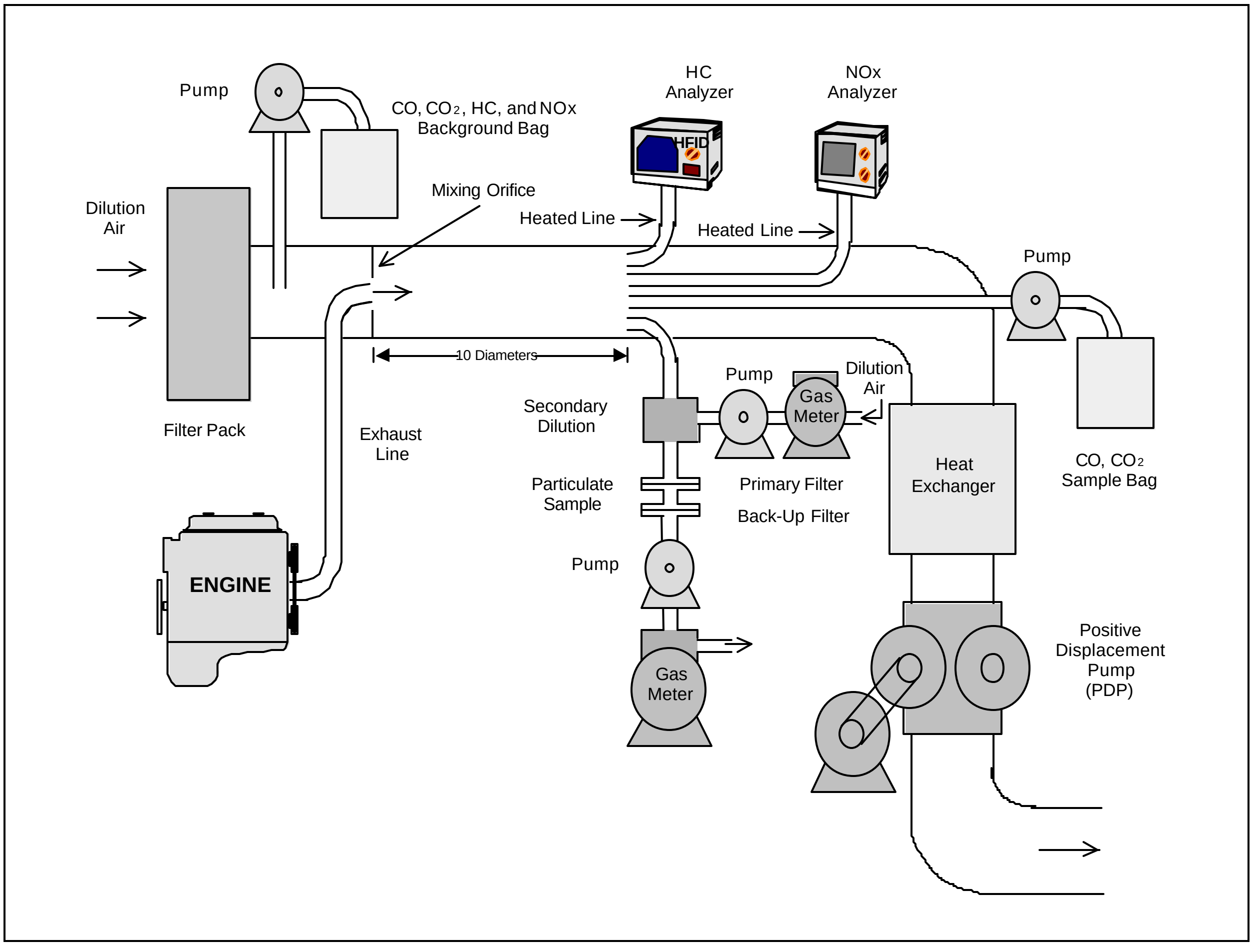

Figure 4. Constant volume sampler setup for emissions measurement.

3.4 Deviations from the Test/QA Plan

Only one baseline test was originally planned using LSD fuel; however, due to a lower than expected baseline emissions level, the vendor requested a second baseline test (one cold start and three hot starts). The cold start for this second baseline test failed the y intercept requirement of the speed regression line, described in Figure N90-11 of 40 CFR, Part 86, Subpart No. 86.1341-90,[11] by 3 rpm. While, the cold start failed statistics by a minor amount, SwRI voided this test and repeated the second baseline. Both the first baseline test and the repeated second baseline test were judged as valid data and were averaged.

3.5 Documented Test Conditions

Engine Performance

Table 3 summarizes observed power and torque for all baseline and control configurations. The engine performance was similar for all configurations. The coefficient of variation was less than one percent for both rated power at a rated speed of 1,800 rpm and for peak torque at 1,200 rpm. The torque map performances for all DOC muffler configuration tests were similar, with a coefficient of variation of less than two percent.

Table 3. Engine Performance Data

Fuel	Test Date	Test Number	Test Type	Rated Power[a] bhp (kW)	Peak Torque[b] lb-ft (N-m)
LSD	10/30/2002	4712-BO-P1	Baseline	405 (302)	1182 (1602)
	10/31/2002	4712-B22-SC-P1	Controlled	404 (301)	1181 (1600)
	11/1/2002	4712-M11-SC-P1	Controlled	403 (301)	1177 (1575)
	11/9/2002	4712-BO-P2	Baseline	402 (300)	1175 (1592)
Average:				**404 (301)**	**1179 (1597)**
Standard deviation:				**1.3**	**3.3**
Coefficient of variation, %:				**0.3**	**0.3**
ULSD	11/5/2002	4579-BO-P1	Baseline	398 (297)	1162 (1551)
	11/6/2002	4579-B22-SC-P1	Controlled	396 (296)	1160 (1549)
	11/7/2002	4579-B23-O-P1	Controlled	399 (298)	1162 (1551)
Average:				**398 (297)**	**1161 (1550)**
Standard deviation:				**1.5**	**1.2**
Coefficient of variation, %:				**0.4**	**0.1**

[a]Engine power at rated speed of 1,800 rpm.
[b]Engine peak torque at rated speed of 1,200 rpm.

Engine Blow-By Pressure

The engine blow-by pressure was measured at the engine breather port outlet to determine the effect of the baseline BPM measurement on blow-by pressure. It was decided, in order to prevent bias in the BPM measurements or otherwise alter engine emissions, that the blow-by pressure when using the BPM measurement system should not deviate by more than ± 2 in. H_2O (500 Pa) from the level noted during OCC operation without the BPM measurement system in place. It is also important to note that during OCC operation without BPM measurement, the blow-by was routed to the outside of the engine test cell via a 1-in. (2.5-cm) diameter tube that is about 15 ft (4.6 m) in length. The blow-by pressure during operation without the BPM measurement system in place typically was 0.3 in. H_2O (75 Pa) higher at engine idle and up to 2 in. H_2O (500 Pa) higher at high engine speed and load, than during operation with the BPM measurement system. This pressure difference was less than 2 in. H_2O (500 Pa) for more than 99 percent of the second-by-second data.

Engine Exhaust Back-Pressure

The engine exhaust back-pressure was set to 2.8 in. Hg (9.5 kPa) in accordance with the engine manufacturer's specifications for the baseline tests. Each DOC muffler configuration displayed a similar back-pressure of 2.8 in. Hg (9.5 kPa) at rated engine power, except for the aged DOC (M11090) where the backpressure was about 3.8 in. Hg (13 kPa).

Engine Exhaust Temperature

Temperature measurements were made in the exhaust system at the inlet and outlet of the DOC. The temperature probes were located five in. upstream of the DOC inlet and ten in. downstream of the DOC outlet. Typical temperatures averaged over the transient test cycle were 470 to 480 °F (240 to 250 °C) at the DOC inlet and 510 to 530 °F (270 to 280 °C) at the DOC outlet.

Fuel Consumption

Table 4 presents the brake specific fuel consumption (BSFC) for all baseline and control configurations.

Table 4. Brake Specific Fuel Consumption

Test Number	Test Type	Test Date	BSFC, lb/bhp-hr	BSFC, kg/kW-hr	Weighted BSFC, lb/bhp-hr	Weighted BSFC, kg/kW-hr
First engine baseline with LSD fuel						
4712-BO-C1	Cold-start	10/31/02	0.428	0.259		
4712-BO-H1	Hot-start	10/31/02	0.414	0.250	0.416	0.252
4712-BO-H2	Hot-start	10/31/02	0.411	0.249	0.413	0.250
4712-BO-H3	Hot-start	10/31/02	0.410	0.248	0.413	0.250
Second engine baseline with LSD fuel						
4712-BO-C3	Cold-start	11/12/02	0.426	0.258		
4712-BO- H7	Hot-start	11/12/02	0.415	0.251	0.417	0.252
4712-BO-H8	Hot-start	11/12/02	0.415	0.251	0.417	0.252
4712-BO-H9	Hot-start	11/12/02	0.412	0.249	0.414	0.250
Engine baseline with ULSD fuel						
4579-BO-C1	Cold-start	11/06/02	0.434	0.263		
4579-BO-H1	Hot-start	11/06/02	0.416	0.252	0.419	0.253
4579-BO-H2	Hot-start	11/06/02	0.408	0.247	0.412	0.249
4579-BO-H3	Hot-start	11/06/02	0.418	0.253	0.420	0.254
Degreened DOC Series 6000, Spiracle™, and LSD fuel						
4712-B22-SC-C1	Cold-start	11/01/02	0.432	0.261		
4712-B22-SC-H1	Hot-start	11/01/02	0.414	0.250		
4712-B22-SC-H2	Hot-start	11/01/02	0.412	0.249		
4712-B22-SC-H3	Hot-start	11/01/02	0.414	0.250		
Aged DOC Series 6000, Spiracle™, and LSD fuel						
4712-M11-SC-C1	Cold-start	11/05/02	0.435	0.263		
4712-M11-SC-H1	Hot-start	11/05/02	0.414	0.250		
4712-M11-SC-H2	Hot-start	11/05/02	0.411	0.249		
4712-M11-SC-H3	Hot-start	11/05/02	0.411	0.249		
Degreened DOC Series 6000, Spiracle™, and ULSD fuel						
4579-B22-SC-C1	Cold-start	11/07/02	0.423	0.256		
4579-B22-SC-H1	Hot-start	11/07/02	0.414	0.250		
4579-B22-SC-H2	Hot-start	11/07/02	0.401	0.243		
4579-B22-SC-H3	Hot-start	11/07/02	0.409	0.247		

Section 4.0
Summary and Discussion of Emission Results

The baseline and controlled emissions data are summarized in Tables 5a through 5d. The emissions were measured at each test point for HC, CO, NO_x, and PM. Tables 5a through 5d also provide data on the SOF of the exhaust PM during baseline tests, speciation of the NO_x emissions, CO_2 emissions, and work. For each pollutant and each cold- or hot-start test, the mass emissions per work (bhp-hr) was calculated. The transient composite-weighted emissions were then calculated following the fractional calculation for highway engines to provide composite emissions rates for each pollutant, hot-start test combination as follows.

$$(E_{COMP})_m = 1/7 \cdot E_{COLD} + 6/7 \cdot (E_{HOT})_m \qquad (1)$$

where:

m = 1, 2, or 3 hot-start tests
E_{COMP} = composite emissions rate, g/bhp-hr
E_{COLD} = cold-start emissions rate, g/bhp-hr
E_{HOT} = hot-start emissions rate, g/bhp-hr

These composite emissions rates were then used to calculate the mean and standard deviations for the baseline and controlled emissions rates. These data were in turn used to calculate mean emissions reductions and 95 percent confidence limits. These calculations are based on the generic verification protocol[1] and test/QA plan.[5] However, this calculation procedure differed slightly from the equation in the CFR[8] in the order of the calculation. The CFR specifies that the mass emissions in grams and the work in bhp-hr are first weighted for the cold- and hot-start tests before the mass emissions are divided by the work.

Exhaust PM and BPM emissions were separately measured for every cold-start and hot-start FTP transient baseline test performed in this program. BPM emissions were added to exhaust PM emissions to calculate a baseline of total particulate matter (TPM) emissions for comparison to the exhaust PM emissions for this test where the engine was equipped with a DOC muffler and the Spiracle™ Closed Crankcase Filtration System.

Table 6 summarizes the composite weighted emission values and Table 7 the verified emissions reductions and their 95 percent confidence limits. As shown in Table 7, the mean emissions reductions for PM emissions ranged from 21 to 34 percent depending on the type of device (degreened or aged) and fuel used. The mean emissions reductions for NO_x did not show a significant change. For HC, it ranged from 50 to 62 percent, and for CO, it ranged from 12 to 24 percent.

Table 5a. Baseline Emissions Test Data (English units)

Test Number	Test Type	Test Date	g/bhp-hr						NO_2/ NO_X, %	g/bhp-hr			Work, bhp-hr
			Exhaust PM	SOF	Blow-By PM	NO_X	NO	NO_2 [a]		HC	CO	CO_2	
First engine baseline with LSD fuel and open crankcase configuration													
4712-BO-C1	Cold-start	10/31/02	0.132	0.081	0.009	3.96	3.50	0.46	11.7	0.443	1.87	612	29.52
4712-BO-H1	Hot-start	10/31/02	0.070	0.029	0.014	3.91	3.41	0.51	13.0	0.096	1.05	594	29.58
4712-BO-H2	Hot-start	10/31/02	0.072	0.031	0.015	3.93	3.41	0.52	13.3	0.106	1.02	589	29.62
4712-BO-H3	Hot-start	10/31/02	0.073	0.015	0.015	3.90	3.36	0.54	13.8	0.105	1.05	587	29.53
Second engine baseline with LSD fuel and open crankcase configuration													
4712-BO-C3	Cold-start	11/12/02	0.093	0.04	0.009	4.08	3.60	0.48	11.7	0.238	1.55	610	29.61
4712-BO-H7	Hot-start	11/12/02	0.077	0.025	0.012	4.04	3.52	0.52	12.8	0.181	1.03	594	29.61
4712-BO-H8	Hot-start	11/12/02	0.076	0.024	0.013	4.01	3.49	0.51	12.8	0.201	0.98	595	29.60
4712-BO-H9	Hot-start	11/12/02	0.08	0.026	0.013	4.01	3.48	0.53	13.2	0.281	0.97	591	29.72
Engine baseline with ULSD fuel and with open crankcase configuration													
4579-BO-C1	Cold-start	11/06/02	0.122	0.089	0.009	4.00	3.49	0.51	12.8	0.753	2.14	618	29.40
4579-BO-H1	Hot-start	11/06/02	0.066	0.020	0.013	3.97	3.41	0.56	14.1	0.197	1.03	596	29.32
4579-BO-H2	Hot-start	11/06/02	0.067	0.019	0.014	3.99	3.46	0.53	13.3	0.194	1.03	585	29.30
4579-BO-H3	Hot-start	11/06/02	0.065	0.017	0.015	3.98	3.44	0.53	13.3	0.209	1.00	599	29.32

[a] NO_2 calculated as NO_x - NO.

Table 5b. Baseline Emissions Test Data (metric units)

Test Number	Test Type	Test Date	g/kWh						NO_2/ NO_x, %	g/kWh			Work, kWh
			Exhaust PM	SOF	Blow-By PM	NO_x	NO	NO_2[a]		HC	CO	CO_2	
First engine baseline with LSD fuel and open crankcase configuration													
4712-BO-C1	Cold-start	10/31/02	0.176	0.108	0.012	5.28	4.67	0.61	11.7	0.591	2.49	815	22.14
4712-BO-H1	Hot-start	10/31/02	0.093	0.039	0.019	5.21	4.55	0.68	13.0	0.128	1.40	792	22.19
4712-BO-H2	Hot-start	10/31/02	0.096	0.041	0.020	5.24	4.55	0.69	13.3	0.141	1.36	785	22.22
4712-BO-H3	Hot-start	10/31/02	0.097	0.020	0.020	5.20	4.48	0.72	13.8	0.140	1.40	783	22.15
Second engine baseline with LSD fuel and open crankcase configuration													
4712-BO-C3	Cold-start	11/12/02	0.124	0.053	0.012	5.44	4.80	0.64	11.7	0.317	2.07	813	22.21
4712-BO-H7	Hot-start	11/12/02	0.103	0.033	0.016	5.39	4.69	0.69	12.8	0.241	1.37	792	22.21
4712-BO-H8	Hot-start	11/12/02	0.101	0.032	0.017	5.35	4.65	0.68	12.8	0.268	1.31	793	22.20
4712-BO-H9	Hot-start	11/12/02	0.107	0.035	0.017	5.35	4.64	0.71	13.2	0.375	1.29	788	22.29
Engine baseline with ULSD fuel and open crankcase configuration													
4579-BO-C1	Cold-start	11/06/02	0.163	0.119	0.012	5.33	4.65	0.68	12.8	1.004	2.85	824	22.05
4579-BO-H1	Hot-start	11/06/02	0.088	0.027	0.017	5.29	4.55	0.75	14.1	0.263	1.37	795	21.99
4579-BO-H2	Hot-start	11/06/02	0.089	0.025	0.019	5.32	4.61	0.71	13.3	0.259	1.37	780	21.98
4579-BO-H3	Hot-start	11/06/02	0.087	0.023	0.020	5.31	4.59	0.71	13.3	0.279	1.33	799	21.99

[a] NO_2 calculated as NO_x - NO.

Table 5c. Controlled Emissions Test Data (English units)

Test Number	Test Type	Test Date	g/bhp-hr						NO_2/ NO_X, %	g/bhp-hr			Work, bhp-hr
			Exhaust PM	SOF	Blow-By PM	NO_X	NO	NO_2[a]		HC	CO	CO_2	
Degreened DOC (B2246), CCC with Spiracle™, and LSD fuel													
4712-B22-SC-C1	Cold-start	11/01/02	0.098	[b]	[c]	4.09	3.79	0.30	7.3	0.248	1.84	618	29.63
4712-B22-SC-H1	Hot-start	11/01/02	0.062	[b]	[c]	3.95	3.67	0.28	7.0	0.040	.75	595	29.65
4712-B22-SC-H2	Hot-start	11/01/02	0.063	[b]	[c]	3.90	3.58	0.32	8.3	0.060	.82	591	29.60
4712-B22-SC-H3	Hot-start	11/01/02	0.067	[b]	[c]	3.94	3.65	0.28	7.2	0.090	.88	594	29.63
Aged DOC (M110940), CCC with Spiracle™, and LSD fuel													
4712-M11-SC-C1	Cold-start	11/05/02	0.102	[b]	[c]	4.07	3.85	0.21	5.3	0.242	1.68	622	29.75
4712-M11-SC-H1	Hot-start	11/05/02	0.068	[b]	[c]	3.87	3.61	0.26	6.8	0.020	0.858	594	29.51
4712-M11-SC-H2	Hot-start	11/05/02	0.071	[b]	[c]	3.91	3.65	0.26	6.8	0.070	0.889	590	29.64
4712-M11-SC-H3	Hot-start	11/05/02	0.069	[b]	[c]	3.84	3.57	0.27	7.0	0.040	0.835	590	29.58
Degreened DOC (B2246), CCC with Spiracle™, and ULSD fuel													
4579-B22-SC-C1	Cold-start	11/07/02	0.074	[b]	[c]	4.07	3.82	0.25	6.1	0.329	1.62	605	29.30
4579-B22-SC-H1	Hot-start	11/07/02	0.063	[b]	[c]	3.95	3.70	0.25	6.3	0.131	0.78	594	29.31
4579-B22-SC-H2	Hot-start	11/07/02	0.057	[b]	[c]	3.89	3.66	0.23	5.9	0.116	0.79	575	29.32
4579-B22-SC-H3	Hot-start	11/07/02	0.058	[b]	[c]	3.92	3.71	0.21	5.5	0.075	0.77	587	29.31

[a] NO_2 calculated as NO_x - NO.
[b] Measurement not ocnducted.
[c] Not applicable

Table 5d. Controlled Emissions Test Data (metric units)

Test Number	Test Type	Test Date	g/kWh						NO₂/NOx, %	g/kWh			Work, kWh
			Exhaust PM	SOF	Blow-By PM	NO_X	NO	NO_2 [a]	NO_2/NO_X, %	HC	CO	CO_2	
Degreened DOC (B2246), CCC with Spiracle™, and LSD fuel													
4712-B22-SC-C1	Cold-start	11/01/02	0.131	[b]	[c]	5.45	5.05	0.40	7.3	0.331	2.45	824	22.22
4712-B22-SC-H1	Hot-start	11/01/02	0.083	[b]	[c]	5.27	4.89	0.37	7.0	0.053	1.00	793	22.24
4712-B22-SC-H2	Hot-start	11/01/02	0.084	[b]	[c]	5.20	4.77	0.43	8.3	0.080	1.09	788	22.20
4712-B22-SC-H3	Hot-start	11/01/02	0.089	[b]	[c]	5.25	4.87	0.37	7.2	0.120	1.17	792	22.22
Aged DOC (M110940), CCC with Spiracle™, and LSD fuel													
4712-M11-SC-C1	Cold-start	11/05/02	0.136	[b]	[c]	5.43	5.13	0.28	5.3	0.323	2.24	829	22.31
4712-M11-SC-H1	Hot-start	11/05/02	0.091	[b]	[c]	5.16	4.81	0.35	6.8	0.027	1.15	792	22.13
4712-M11-SC-H2	Hot-start	11/05/02	0.095	[b]	[c]	5.21	4.87	0.35	6.8	0.058	1.19	787	22.23
4712-M11-SC-H3	Hot-start	11/05/02	0.092	[b]	[c]	5.12	4.76	0.36	7.0	0.053	1.12	787	22.19
Degreened DOC (B2246), CCC with Spiracle™, and ULSD fuel													
4579-B22-SC-C1	Cold-start	11/07/02	0.099	[b]	[c]	5.43	5.09	0.33	6.1	0.439	2.16	807	21.98
4579-B22-SC-H1	Hot-start	11/07/02	0.084	[b]	[c]	5.27	4.93	0.33	6.3	0.175	1.04	792	21.98
4579-B22-SC-H2	Hot-start	11/07/02	0.076	[b]	[c]	5.19	4.88	0.31	5.9	0.155	1.05	767	21.99
4579-B22-SC-H3	Hot-start	11/07/02	0.077	[b]	[c]	5.23	4.95	0.28	5.5	0.100	1.03	783	21.98

[a] NO_2 calculated as NO_x - NO.
[b] Measurement not conducted.
[c] Not applicable

Table 6. Summary of Verification Test Emission Levels

Device type	Fuel		Composite Weighted Emission Value, g/bhp-hr (g/kWh)									
	Baseline	Controlled	Baseline					Controlled				
			PM	NO_x	HC	CO	CO_2	PM	NO_x	HC	CO	CO_2
Degreened	LSD	LSD	0.093 (0.124)	4.0 (5.3)	0.19 (0.25)	1.1 (1.5)	594 (792)	0.069 (0.092)	4.0 (5.3)	0.090 (0.120)	0.96 (1.28)	597 (796)
Aged	LSD	LSD	0.093 (0.124)	4.0 (5.3)	0.19 (0.25)	1.1 (1.5)	594 (792)	0.074 (0.099)	3.9 (5.2)	0.072 (0.096)	0.98 (1.31)	596 (795)
Degreened	LSD	ULSD	0.093 (0.124)	4.0 (5.3)	0.19 (0.25)	1.1 (1.5)	594 (792)	0.061 (0.081)	3.9 (5.2)	0.14 (0.19)	0.90 (1.20)	588 (784)
Degreened	ULSD	ULSD	0.087 (0.116)	4.0 (5.3)	0.28 (0.37)	1.2 (1.6)	597 (796)	0.061 (0.081)	3.9 (5.2)	0.14 (0.19)	0.90 (1.20)	588 (784)

Table 7. Summary of Verification Test Emission Reductions

	Fuel		Mean Emissions Reduction [a] (%)				95% Confidence Limits on the Emissions Reduction (%)			
Device type	Baseline	Controlled	PM	NO_x	HC	CO	PM	NO_x	HC	CO
Degreened	LSD	LSD	26	[b]	52	14	23–30	[b]	23-81	5.1-22
Aged	LSD	LSD	21	[b]	62	12	19-23	[b]	33-90	7.1-18
Degreened	LSD	ULSD	34	[b]	[b]	19	30-38	[b]	[b]	15-24
Degreened	ULSD	ULSD	30	[b]	50	24	24-36	[b]	41-60	20-27

[a] Emissions reduction from baseline of tailpipe plus crankcase.
[b] The emissions reduction could not be distinguished from zero with 95% confidence.

4.1 Quality Assurance

The environmental technology verification of the DOC muffler and Spiracle™ blow-by control device for heavy-duty diesel engines was performed in accordance with the test/QA plan.[5] An audit of data quality included the review of equipment, personnel qualifications, procedures, record keeping, data validation, analysis, and reporting. Preliminary, in-process, and final inspections, and a review of 10 percent of the data showed that the requirements stipulated in the test/QA plan[5] were achieved. The APCTVC's quality manager reviewed the test results and the quality control data and concluded that the data quality objectives given in the generic verification protocol have been attained. EPA and RTI quality assurance staff conducted audits of SwRI's technical and quality systems in April 2002 and found no deficiencies that would adversely impact the quality of results. The equipment was appropriate for the verification testing, and it was operating satisfactorily. SwRI's technical staff are well qualified to perform the testing and conduct themselves in a professional manner.

Section 5.0
References

1. Research Triangle Institute. *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*. Research Triangle Park, NC, January 2002.

2. Research Triangle Institute. *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Donaldson Company, Inc. DOC Converter Muffler*. Research Triangle Park, NC, October 2002.

3. Southwest Research Institute. *Environmental Technology Verification of Several Diesel Oxidation Catalyst Mufflers and a Spiracle Blow-By Emission Control Device for Heavy-Duty Diesel Engines*. San Antonio, TX, December 2002.

4. Southwest Research Institute. *Audit of Data Quality for Environmental Technology Verification of Several Diesel Oxidation Catalyst Mufflers and a Spiracle™ Blow-By Emission Control Device for Heavy-Duty Diesel Engines*. San Antonio, TX, January 2003.

5. Research Triangle Institute. *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines.* Research Triangle Park, NC, April 2002.

6. Fuel specifications, 40 CFR § 86.1313-98, Table N98-2 (updated July 2001).

7. Fuel specifications, 40 CFR § 86.1313-2007, Table N07-2 (updated January 2001).

8. 40 CFR § 86, Subpart N, as of July 1, 1999, http://www.epa.gov/epahome/cfr40.htm

9. Southwest Research Institute. Standard Operating Procedure 07-043, Blow-By Emissions Measurement of Heavy-Duty Diesel Engines in *Environmental Technology Verification of Several Diesel Oxidation Catalyst Mufflers and a Spiracle Blow-By Emission Control Device for Heavy-Duty Diesel Engines*. San Antonio, TX, December 2002.

10. California Air Resources Board. *Test Method for Soluble Organic Fraction (SOF) Extraction*, El Monte, CA, April, 1989.

11. 40 CFR, § 86.1341-90, Figure N90-11 (as amended September 5, 1997), http://www.access.gpo.gov/nara/cfr/cfrhtml_00/Title_40/40cfr86a_00.html